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An Assessment Framework for Pacific Herring (*Clupea pallasi*) stocks in British Columbia

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Cadre d’évaluation pour les harengs du Pacifique (*Clupea pallasi*) en Colombie-Britannique

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ABSTRACT

Herring stock abundance in British Columbia waters is assessed using an age structured assessment model for the major stock assessment regions and an escapement model for the minor stocks in Areas 2W and 27. These models have been applied to assess herring abundance since 1984. Accurate estimates of current and future stock abundance rely heavily on consistent and reliable biological sampling of the populations. Extensive SCUBA surveys are conducted throughout the British Columbia coast to enumerate the numbers of fish spawning in each area and this information forms an important part of the data for determining total abundance in the age-structured model. Additional data on total harvest, fish size and age structure of the spawning runs are used to determine current abundance levels. As in recent assessments a fixed spawn conversion or catchability factor is applied for the dive survey era beginning in 1988 and a free fitted parameter is estimated for the earlier surface survey period. In addition, a year specific logistic function is applied to model the availability of fish on the spawning grounds. Forecasts of future stock abundance are developed from estimates of historical recruitment and used to provide advice on allowable harvest. The harvesting policy permits a maximum of up to 20% removal of the forecast spawning biomass provided the abundance is greater than the fishing threshold or Cutoff level established to conserve biomass in periods of reduced productivity.

RÉSUMÉ

On évalue l’abondance du hareng dans les eaux de la Colombie-Britannique à l’aide d’un modèle de la structure par âge, pour les principales zones d’évaluation des stocks, et d’un modèle des échappées, pour les stocks moins importants des zones 2W et 27. Ces modèles sont utilisés pour évaluer l’abondance du hareng depuis 1984. La précision des estimations de l’abondance actuelle et future repose fortement sur un échantillonnage biologique uniforme et fiable des populations. Des plongeurs mènent des relevés exhaustifs le long de la côte de la Colombie-Britannique pour dénombrer les poissons qui fraient dans chaque zone. L’information ainsi recueillie représente une partie importante des données que l’on utilise pour déterminer l’abondance totale avec le modèle de la structure par âge. On utilise des données supplémentaires sur les prélèvements totaux, la taille des poissons et la structure par âge des bancs de reproducteurs pour déterminer les niveaux d’abondance actuels. Comme dans les évaluations récentes, on applique un facteur fixe de conversion des indices de frai ou de capturabilité pour les relevés des plongeurs effectués depuis 1988 ainsi qu’un paramètre ajusté librement des indices issus des relevés antérieurs effectués depuis la surface. En outre, une fonction logistique annuelle est appliquée pour modéliser la disponibilité des poissons dans les frayères. On élabore des prévisions de l’abondance future à partir d’estimations du recrutement antérieur que l’on utilise ensuite pour formuler un avis sur les prélèvements admissibles. La politique sur les prélèvements permet des prélèvements atteignant 20 % de la biomasse du stock reproducteur prévue pourvu que l’abondance soit supérieure au seuil de pêche ou le niveau d’arrêt de la pêche établi pour préserver la biomasse dans les périodes de productivité réduite.

1. INTRODUCTION

Herring have been one of the most important components of the British Columbia commercial fishery over the past century with catch records dating from 1877. The fishery evolved from a dry salted product in the early 1900s, to a reduction fishery in the 1930s that collapsed in the late 1960s as a result of environmental change and excessive harvesting. After a four year closure the current roe fishery began in 1972. Roe fisheries occur just prior to spawning when the fish are highly aggregated and very vulnerable to exploitation. Since 1983, herring roe fisheries have been managed with a fixed harvest rate policy and a quota system. Under this system, harvest levels are determined prior to the season based on a fixed percentage (20%) of forecast stock size. In addition, threshold biomass or Cutoff levels were introduced in 1986 to restrict harvest during periods of reduced abundance. Stocker (1993) provides a detailed description of the fishery management framework.

Since the mid-1980s stock assessments had been conducted with two analytical models developed explicitly for British Columbia herring populations: (1) a modification of the escapement model described by Schweigert and Stocker (1988); and (2) a modification of the age-structured model described by Fournier and Archibald (1982). In 2002, the age-structured model was adopted as the primary assessment tool for the major migratory stocks while the escapement model estimates are provided for minor stocks in Areas 2W and 27. The assessment framework presented here outlines the data and methods utilized to provide an annual assessment of current abundance and forecasts of run size for the next fishing season

1.1. STOCK CONSIDERATIONS

The stock concept used for managing the British Columbia herring resource is based on current knowledge of stock structure that is necessarily incomplete. Given incomplete knowledge of population structure, it is prudent to manage fisheries to ensure maintenance of the greatest potential biological diversity in all regions. Additionally, stock forecasts for smaller geographic regions than those used in the current assessments are not accurate enough for fisheries management. Therefore, fisheries should continue to focus on the major aggregations within each assessment region to minimize the potential over-exploitation of any smaller, spatially discrete spawning groups. Recent coded wire tagging and micro-satellite DNA genetic studies support a meta-population model of stock structure comprised of five major migratory sub-populations targeted by the roe and other fisheries (Schweigert and Flostrand 2000, Flostrand and Schweigert 2002, 2003, 2004, Beacham et al. 2001, 2002, Ware and Schweigert 2001, 2002).

The stock groupings used for the current assessments are identical to those used since 1993 (Fig. 1.). The Queen Charlotte Islands stock assessment region includes most of Statistical Area 2E, spanning from Cumshewa Inlet in the north to Louscoone Inlet in the south. The Prince Rupert District stock assessment region encompasses Statistical Areas 3 to 5. The Central Coast assessment region separates the major migratory stocks from the minor spawning populations in the mainland inlets. The Central Coast assessment region includes Statistical Area 7 plus Kitasu Bay in Area 6, Kwakshua Channel in Area 8. The Strait of Georgia stock assessment region includes all of Statistical Areas 14 to 19, 28, 29, and Deepwater Bay and Okisollo Channel in Area 13. The west coast of Vancouver Island assessment region encompasses Statistical Areas 23 to 25. Midgley (2003) outlines current geographical stock boundaries.

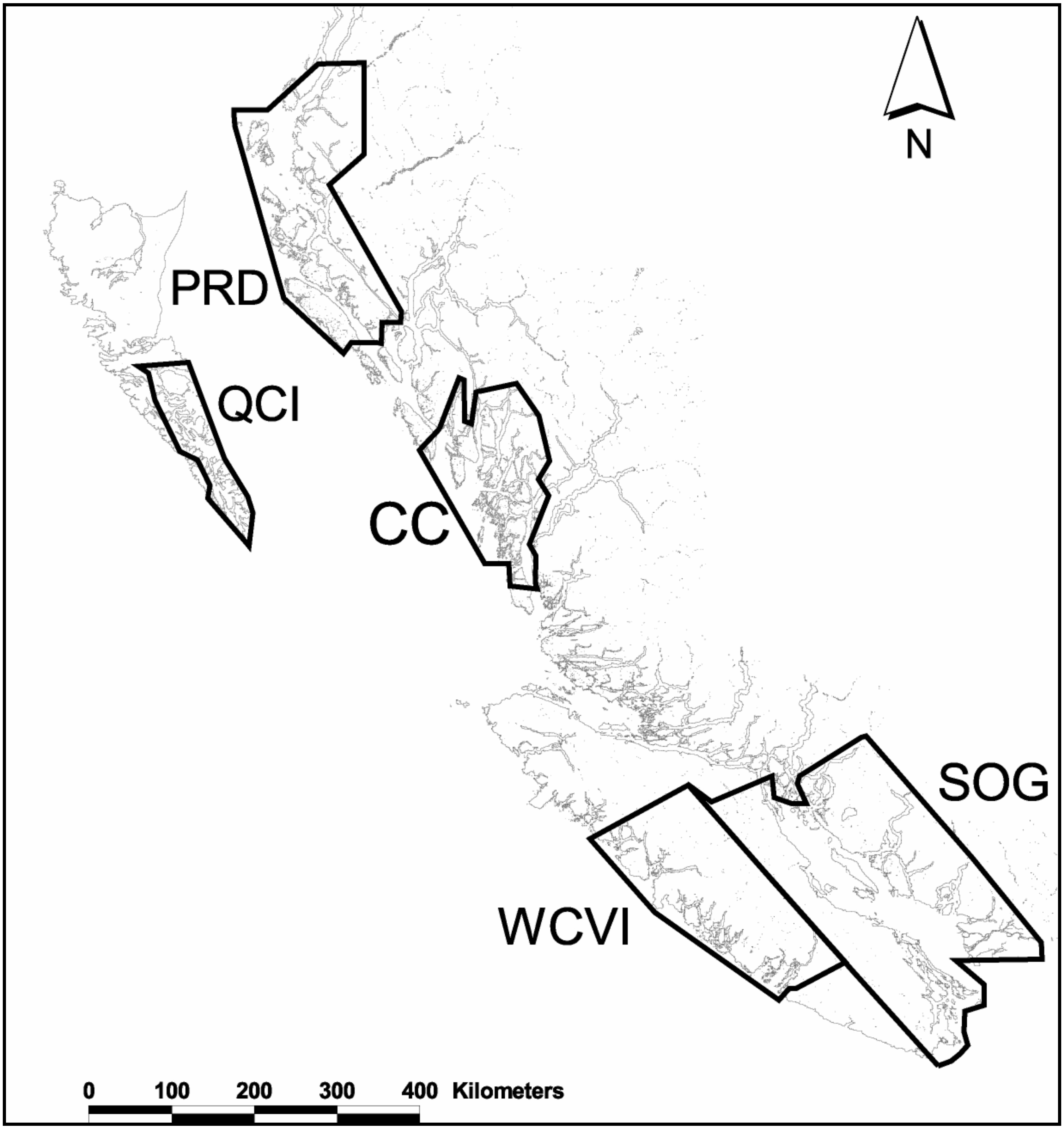

Figure 1. The five major British Columbia herring stock assessment regions: Prince Rupert District (PRD), Queen Charlotte Islands (QCI), Central Coast (CC), west coast Vancouver Island (WCVI) and the Strait of Georgia (SOG).

Abundance estimates are not regularly developed for areas outside of the major assessment regions that may support additional small herring runs, because both the spawn survey and catch data are incomplete for many of these areas. Therefore, presentation of stock estimates could lead to erroneous conclusions regarding either absolute abundance or stock trends. Recent attempts to conduct a complete age-structured assessment for Areas 2W and 27 have been unsuccessful because of incomplete data. An escapement model estimate of current stock abundance is available for these areas but no reliable forecast of abundance in the coming year is possible.

1.2. DATA BASE

The primary data sources for the stock assessments are spawn survey data, commercial catch landings data, and age composition data from biological samples of commercial fishery, pre-fishery charter, and research catches. These data are available in an Access database for the period 1951 to present. This time span includes the reduction fishery period to 1968 and the subsequent roe fishery period that began in 1972.

Of the three data sets, the spawn data contain the largest measurement errors. While the quality of spawn surveys has generally improved over the course of the time series, due to increased effort and better quality control of the surveys, there are occasional problems with equipment and weather that may hamper data completeness or accuracy in some years. The consistent observations made during all years of surveys are the total length, the average width, and a measure of egg density for each spawning site. Since 1987 an increasing number of egg beds have been assessed using SCUBA rather than traditional surface survey methods. We believe that the SCUBA data provide a relatively more accurate estimate of spawn bed length, width, and egg density than earlier surface surveys. These data have been used in developing the spawn index where available.

Catch information is obtained from landing slips or monitoring of plant offload data. Historically, landing slip data were summed by fishery season (seasons run from July 1 to June 30). Beginning in 1997/98 season, roe catch figures are based on verified plant offload weights, a result of the introduction of the individual vessel quota (‘pool fishery’) system for all fisheries except the Strait of Georgia and Prince Rupert gillnet fisheries. Since the 1998/99 season, verified plant offload weights are available for all food and roe fisheries coast-wide. Historical catch taken in all non-SOK fisheries are shown in Figure 2 and for roe fisheries in each assessment region in Appendix Table 1.

The spawn-on-kelp (SOK) fishery currently consists of 46 licensed operators that have been allocated about 3000 tons (2722 tonnes) of herring in recent years, for use in open and closed pond operations. For assessment purposes, it is assumed that the 100 tons (91 tonnes) of herring allocated to each closed pond operator are removed from the population as egg production or mortality (Shields et al. 1985). A similar assumption of 35 tons (32 tonnes) is made for open pond operations. These data are treated as an additional seine removal. Allocations to all SOK fisheries since its inception in 1975 have been tabulated and are included in the assessment.

Age structure data are used in both assessment models (Figure 3). The information from biological samples of the catch is used for years when there were commercial fisheries. Pre-fishery seine charters began in 1975 and samples from these surveys are used in addition to samples taken from the catch, particularly in areas with no fisheries, or when catch samples are few in number or not representative of the entire catch. Additional data used in both models are annual estimates of the mean weight-at-age. Historically, the target for biological sampling was 400 samples collected coastwide. Recent reduction in ageing capacity has limited biological sample collection to fewer than 300 samples annually.

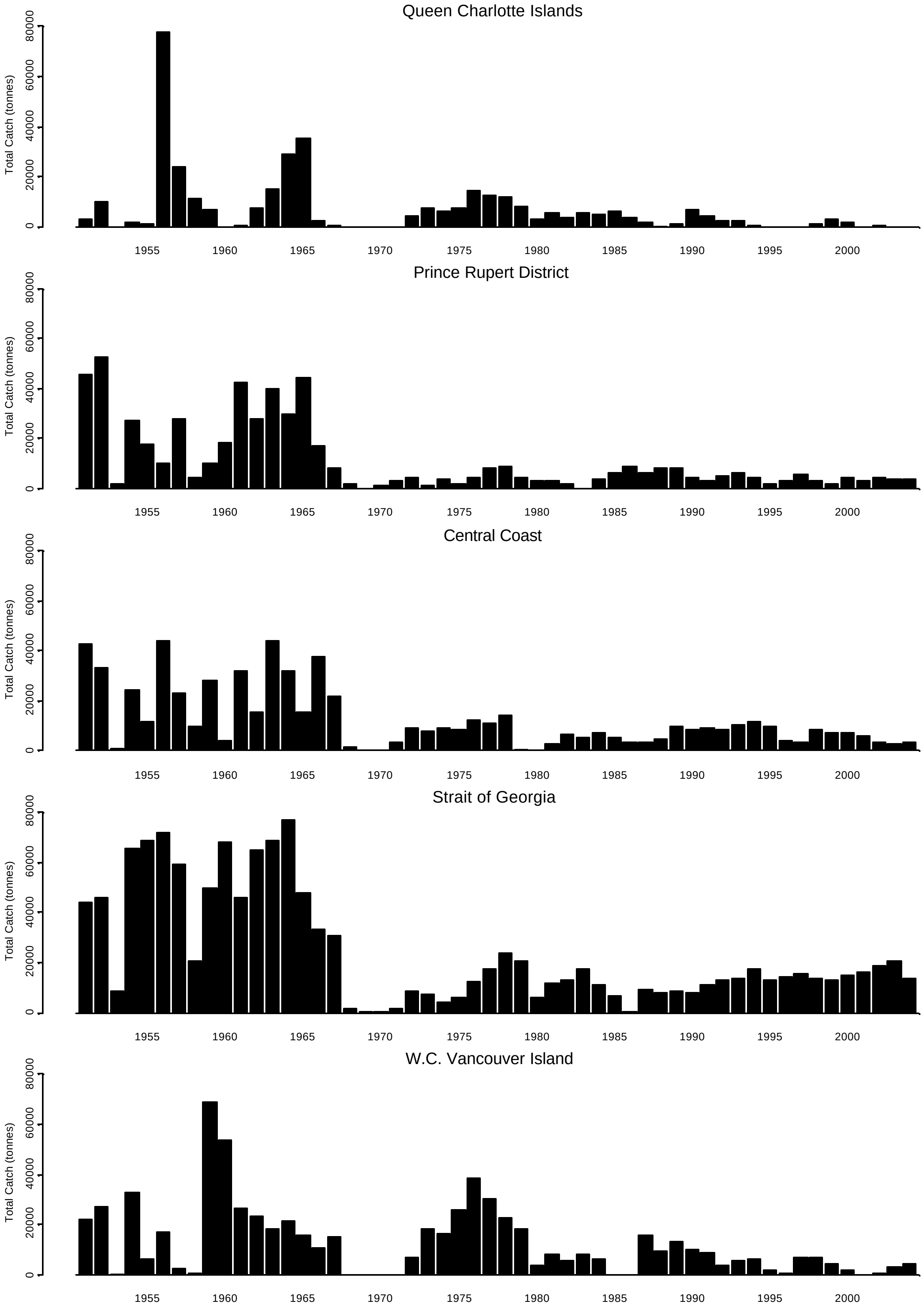

Figure 2. Estimated total catch from all fisheries except spawn-on-kelp for each assessment region from 1951-2005.

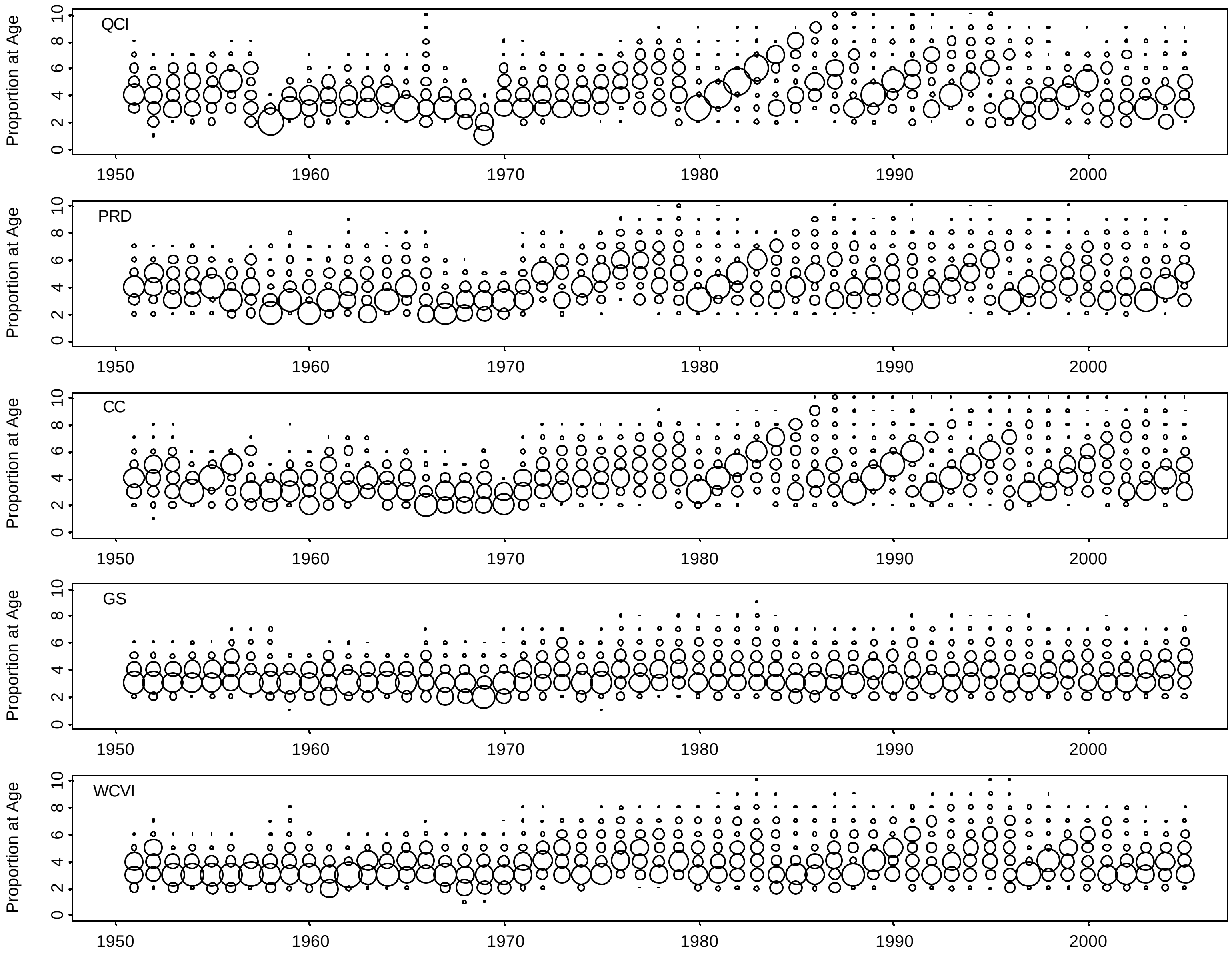

Figure 3. Age composition estimates for five major assessment regions from 1951-2005.

2. SPAWN INDEX

2.1 INTRODUCTION

The spawn index estimation was referred to as the escapement model in earlier assessments. It provides the auxiliary information for tuning the age-structured model. It was first developed for the 1984 assessments (Haist et al. 1985; Schweigert and Stocker 1988), and provides an empirical estimate of the escapement from the fishery based on egg deposition information. For most stock assessment regions, recent estimates of escapement are based primarily on SCUBA survey data. SCUBA surveys have been used routinely on the south coast since 1987 and coast-wide the following year. SCUBA surveys have been found to be superior to surface surveys for spawn assessment because they provide more accurate estimates of both spawn bed width and the intensity of egg deposition. A summary of the recent spawn survey coverage for the British Columbia coast is presented below. As a result of reductions in DFO resources and the consequent contracting of diving surveys to industry, there has been virtually no DFO effort directed to surface surveys since the late 1990s, particularly outside of the assessment regions.

2.2 METHODS

The spawn index provides an estimate of the total egg deposition and by inference an estimate of the pre-fishery mature biomass in each assessment region. The total egg deposition is an amalgamation of estimates of the total number of eggs based on surface surveys, dive surveys of the algal and bottom substrate, and surveys of the giant kelp, *Macrocystis* sp., and attached eggs. The methods adopted for deriving total egg deposition are detailed below.

Surface Surveys

Since the late 1920s, there have been organized efforts to assess the amount of herring eggs deposited throughout the British Columbia coast as an indicator of stock abundance. The parameters which have been monitored consistently are total length of each spawning bed measured parallel to the shoreline, the average width of each spawning bed, and an estimate of the intensity of spawn deposition. Prior to 1981, intensity was estimated subjectively on either a 1-5 or 1-9 scale of light to heavy (Hay and Kronlund 1987). Subsequently, intensity of egg deposition was recorded as the number of egg layers observed on each of several types of algal substrate. Dual observations of layers and intensity were available in most areas for a couple of seasons to permit conversion of the historical intensity estimates to layers of eggs. Beginning in 1987 an increasing proportion of the spawning beds coast-wide have been surveyed using SCUBA techniques as outlined below.

To provide a consistent coast-wide assessment of total egg deposition throughout the time period from 1951 to present, it was necessary to inter-calibrate the surface and SCUBA surveys of egg deposition. Initially, the inter-calibration took the form of linear equations that converted the surface survey estimates of spawning bed width and egg layers to comparable SCUBA estimates (Schweigert and Stocker 1988). However, the data available for this inter-calibration were limited in time and space to particular spawning beds over the course of a few years. As SCUBA surveys of the spawning beds became widespread, an extensive database of estimates of the dimensions of herring spawning beds in most areas of the coast became available and a new procedure for calibrating the width of herring spawning beds estimated by surface surveys was proposed (Schweigert et al. 1993). The methodology consisted of defining spawn pools that were a grouping of herring spawning locations which were geographically adjacent and probably geo-morphologically similar. Hence, diver width estimates developed for such a 'pool' were felt to be characteristic of all herring locations within that pool. For the small number of locations which could not be assigned to a pool, the median width for the herring section (Haist and Rosenfeld 1988) was used to adjust width estimates for the herring location. The median width was preferable to the mean because of the non-normal distribution of the spawn width estimates. Any pools for which fewer than 25 observations of width existed were also adjusted using the section median. For the rare instances where no median estimate was available at the section level, the median width for the assessment region was applied to calculate the area of the egg bed. The long term median spawn width for each pool, was then applied to each surface survey record to estimate a ‘diver’ width and combined with the estimated surface length, to determine the total area of egg deposition for each spawning site.

To estimate egg density, it was assumed that surface and SCUBA survey estimates of the number of egg layers in a spawning bed were equivalent. The database of 5111 observations of egg density per square meter from laboratory egg counts of SCUBA survey quadrat samples collected between 1976-1987 was used to develop a predictive model of egg density from egg layers:

$$Eggs/m^2 = 14.698 + 212.218\ Layers$$

The relationship is statistically significant ($P<0.001$). Total egg deposition for each egg bed is then estimated from the product of total spawning bed area, and egg density predicted from the average surface egg layer estimate.

At present limited data exist for adjusting surface survey width information in most areas outside the major assessment regions except in a few locations such as Johnstone Strait (Statistical Areas 9-13) where some dive surveys have been conducted. These surveys indicated that no adjustments are required for the spawn widths in Johnstone Strait because widths are very narrow and appear to be accurately assessed from the surface in this area (Schweigert and Haegele 1988a, b).

SCUBA Surveys

For SCUBA surveys, spawning bed lengths are determined by exploratory grabs with a spawn drag, rake or snorkelling to define the limits of the areas of egg deposition. A systematic sampling regime is employed whereby transects are set across the egg bed perpendicular to shore at 350 m intervals. Corresponding spawning bed widths are estimated as the mean of all transect lengths within the spawning bed. Estimates of mean egg density are based on a two-stage sampling design (Schweigert et al. 1985, 1990). Average egg density for each spawning bed is estimated, as the weighted mean of the means of a series of quadrats located along each transect, where the weighting is based on the length of each transect. For each quadrat, observations are made on several variables: type of algal substrate; proportion of the quadrat covered by each algal type; number of layers of eggs on each algal type; proportion of the bottom substrate covered by eggs; and an estimate of the number of egg layers on the bottom substrate. In some areas, assessments are also made of the egg deposition on the giant kelp as described in a following section.

Egg deposition for each sampling quadrat is estimated from the predictive equation described in the 1989 assessment report (Haist and Schweigert 1990, Schweigert 1993). The parameters is the current assessment have been re-estimated from the research surveys conducted from the 1981-87 as these data are most consistent with the present survey methodology. Egg density for each vegetation sub-fraction is estimated as follows using non-linear regression (r^2=.4011, P<0.0001).

$$Eggs_{ij} = 600.567\, L_{ij}^{0.6355}\, P_{ij}^{1.4130}\, V_{ij}\, Q_j + e\ .$$

where

$Eggs_{ij}$ = estimated number of eggs in thousands per m^2 on vegetation type *i* in quadrat *j*

L_{ij} = number of layers of eggs on algal substrate *i* in quadrat *j*,
P_{ij} = proportion of quadrat covered by algal substrate *i* in quadrat *j*,
V_{1j} = 0.9715 parameter for sea grasses in quadrat *j*,
V_{2j} = 0.7793 parameter for rockweed in quadrat *j*,
V_{3j} = 0.9119 parameter for flat kelp in quadrat *j*,
V_{4j} = 1.1766 parameter for other brown algae in quadrat *j*,
V_{5j} = 0.6553 parameter for leafy red and green algae in quadrat *j*,
V_{6j} = 1.0000 parameter for stringy red algae in quadrat *j*,
Q_1 = 0.4271 parameter for 1.00 m^2 quadrats,
Q_2 = 1.0512 parameter for 0.50 m^2 quadrats,
Q_3 = 1.0000 parameter for 0.25 m^2 quadrats,
e = normally distributed random variable with mean 0 and variance s^2.

Total egg density (thousands of eggs per m^2) for each quadrat is then estimated by summing the egg density estimates over the vegetation types,

$$Eggs_j = \sum_i Eggs_{ij}.$$

During the period from 1988-1997, samples of algae and the attached eggs from entire quadrats were collected and processed to evaluate model predictions of egg density relative to sample egg counts. Egg counts from these samples did not differ significantly from model predictions. Due to funding shortfalls, no samples have been collected since 1997 and model predictions of egg numbers per sample quadrat are assumed to be unbiased estimates of true egg density.

Eggs on Bottom and *Macrocystis*

Eggs on rock are estimated from the product of the proportion of the quadrat covered by eggs, the number of egg layers, and 340,000 eggs/egg layer/m^2 (Haegele *et al*. 1979). Eggs on rock also includes eggs on other inorganic substrates as well as egg deposition on very short (1-2 cm) red algae, calcareous encrusting algae, worm tubes, logs, etc. Total egg density for each quadrat is the sum of eggs on vegetation plus eggs on rock.

In some northerly areas such as the Queen Charlotte Islands and the Prince Rupert District, a significant proportion of the total egg deposition can occur on the giant kelp, *Macrocystis* sp., with smaller amounts in some localities on the Central Coast and west coast of Vancouver Island. The approach we have adopted for routine SCUBA surveys follows that outlined by Haegele and Schweigert (1985). The SCUBA transects which are used to assess egg density on under-story vegetation are also used to enumerate *Macrocystis* plants and fronds within 1 m on either side of the transect line. An egg prediction equation has been developed (Haegele and Schweigert 1990) to estimate egg numbers for an individual plant ($P<0.0001$, $r^2=78.0$):

$$Eggs/Plant = 0.073\, Layers^{0.673}\, Height^{0.932}\, Fronds^{0.703}$$

where

Eggs/Plant = total number of eggs on the *Macrocystis* plant in millions,
Layers = average number of egg layers on each *Macrocystis* plant,
Height = total height of the *Macrocystis* plant in metres,
Fronds = total number of fronds per *Macrocystis* plant.

This equation estimates the number of eggs occurring on a plant of a specific height with a certain number of fronds and egg layers. In practice, the synoptic SCUBA survey estimates only the average number of egg layers per plant, the average plant height, and the average number of fronds per plant along each transect. These quantities are used in the above equation to estimate the total egg numbers per plant for each transect. These estimates are averaged across transects to obtain an average number of eggs per plant for the entire *Macrocystis* bed.

This information is then combined with the estimate of the density of plants and the estimated area of the *Macrocystis* bed to obtain an estimate of the total number of eggs deposited on the kelp:

$$Total\ Eggs\ on\ Macrocystis = Eggs\ Plant^{-1} \cdot Plants\ m^{-2} \cdot Bed\ Area$$

This egg deposition is then added to the estimated eggs on the understory vegetation to determine a total egg deposition for that spawn pool.

Spawn Index

The spawn index for each major stock is determined by combining the estimates of total egg abundance from the various egg surveys:

$$Index = \frac{SurfaceEggs + UnderstoryEggs + MacrocystisEggs}{100 \cdot Eggs/g \cdot Female \cdot weight}$$

The index provides an estimate of the spawning biomass for each spawning bed that are summed over the entire assessment region to obtain the spawn index that is used as the abundance index in the age-structured model.

Biomass Estimates for Minor Stocks

Biological sampling data and spawn surveys for the minor stocks in Areas 2W and 27 have been intermittent, making age-structured analysis difficult. Alternatively, escapement from the fishery from egg deposition surveys, plus total catch can be used to provide an estimate of the pre-fishery spawning stock biomass for these areas. Similarly to the spawn index, the following relationship may be used to estimate pre-fishery biomass for each area (Schweigert 1993), if all pertinent data are available:

$$B_j = C_j + Eggs_j \bullet \left(\frac{\sum_{3}^{10} P_{ij} W_{ij}}{\sum_{3}^{10} P_{ij} F_{ij} SR_{ij}} \right)$$

where

B_j = total pre-fishery mature biomass in tonnes in year j,
C_j = total catch in tonnes in year j,
$Eggs_j$ = total egg deposition in billions in year j,
P_{ij} = proportion of fish at age i in year j in the spawning run,
F_{ij} = fecundity of females of age i in year j,
SR_{ij} = sex ratio or proportion of females at age i in year j,
W_{ij} = mean weight of fish at age i in year j in tonnes.

However, estimates of fecundity, age composition, and mean weight at age are usually not available each year so a simpler method is used to estimate biomass from the estimate of total egg deposition. Total egg deposition estimates for all spawning beds from all three types of survey (surface, dive, and kelp) are summed within each area and the total egg deposition is converted to tonnes of spawning fish based on an estimate of 100 eggs per gram of herring on average (Hay 1985). The total catch is obtained from sales slip information or verified plant landed weight data and added to the escapement to determine current biomass.

3. AGE-STRUCTURED MODEL

3.1. INTRODUCTION

An age-structured model, based on the error structure proposed by Fournier and Archibald (1982), has been used to assess B.C. herring stocks since 1982. Ongoing revisions to the model have made it more consistent with the life history of herring and the associated fisheries that are analyzed. The current version uses auxiliary information in the form of spawning escapement data, separates catch and age composition data by gear type, and includes availability parameters to estimate partial recruitment to the spawning stock. Model parameters are estimated simultaneously using a maximum likelihood method. The model has used estimates of spawning stock biomass as the abundance or 'spawn index' for parameter estimation beginning in 1994 (Schweigert and Fort 1994). The model is implemented in the C^{++} programming language using AD model builder software (Otter Research Ltd, 2001).

3.2. METHODS

Data Sources

The input data for the age-structured analysis are stored in and summarized from an AccessXP database that is updated annually with new catch, spawn, and bio-sampling information. The data are summarized by fishing season, gear, for three periods for each assessment region.

The Population Model

Purse seines and gillnets are the two types of fishing gear commonly used in B.C. herring fisheries. Seine nets are capable of encircling schools of herring and consequently capture all available age and size classes of herring in a location. Temporal and spatial changes in the distribution of maturing herring schools can affect the composition of seine catches. Nevertheless, seine nets are assumed to be non-selective for herring while gillnets are selective for larger, older fish. Herring fisheries have concentrated primarily on fish which are on, or migrating to the spawning grounds. Therefore, the relative availability of age-classes to non-selective seine gear should be equivalent to the partial recruitment of age-classes to the spawning stock. The age-structured model explicitly separates availability (partial recruitment) and gear selectivity. Seine and gillnet fisheries are usually temporally separate so catch and age-composition are partitioned into fishing periods, separating data for the different gears. Three fishing periods are modelled as follows. The first period encompasses all catch prior to the spring roe herring fisheries. This included reduction fishery catches prior to 1968 and the winter food and bait fisheries since 1970. Most of this catch was taken by seine gear although small amounts were caught with trawl nets (which are also assumed to be non-size selective). The second fishing period includes all seine roe herring catch and the third period includes all gillnet roe herring catch. Beginning with the 2002 assessment, the Access database summarizes catch-at-age data by periods (May-Sept., Oct.-Dec., Jan.-April) that differ slightly from the earlier approach because of a closer correspondence of catch and sampling data during these periods. However, the catch-at-age data are still tabulated into reduction and roe fishery periods consistent with the earlier methodology for further analysis.

In the population model for each assessment region, let T_{ij} be the total number of fish in age class *j* at the beginning of year *i*, where year is equivalent to season, and l_{ij} be the proportion of age *j* fish which are available to the fishery. Then N_{ij1}, the total number of age class *j* fish which are available at the start of period 1 in year *i* is given by

$$N_{ij1} = l_{ij} T_{ij} \text{, where } 0 \langle l_{ij} \langle 1 \qquad 3.1$$

To model the fishing process, a form of the catch equations that models fishing and natural mortality as continuous processes over time period *r*, is used:

$$C_{ijr} = \frac{F_{ijr}}{F_{ijr} + M_r} \left(1 - \exp\left(-F_{ijr} - M_r\right)\right) N_{ijr} \, ,$$

and, for $r < 3$

$$N_{ijr+1} = N_{ijr} \exp\left(-F_{ijr} - M_r\right),$$

where

C_{ijr}	is the catch of age class *j* in year *i* for period *r*,
F_{ijr}	is the fishing mortality of age class *j* in year *i* for period *r*,
M_r	is the natural mortality for period *r*,
N_{ijr}	is the number of fish in age class *j* in year *i* for period *r*,
i	is the year (*i* = 1 to current),
j	is the number of age classes (*j* = 2 to 10),
r	is the number of fishing periods (*r* = 1 to 3).

$N_{i+1,j+1,1}$ is defined by equation 3.1 where for $j+1 < k$

$$T_{i+1,j+1} = N_{ijr} \exp\left(-F_{ijr} - M_r\right) + T_{ij}\left(1 - l_{ij}\right) \exp\left(\sum_r - M_r\right) \qquad 3.2$$

In the model the last age class, *k*, accumulates all fish aged *k* and older, so for $j+1=k$ equation 3.2 is replaced by

$$T_{i+1,k} = N_{i,k-1,r} \exp\left(-F_{i,k-1,r} - M_r\right) + T_{i,k-1}\left(1 - l_{i,k-1}\right) \exp\left(\sum_r - M_r\right)$$
$$+ N_{ikr} \exp\left(-F_{ikr} - M_r\right) + T_{ik}\left(1 - l_{ik}\right) \exp\left(\sum_r - M_r\right)$$

To reduce the number of parameters to be estimated, assumptions are made about the form of the availabilities and mortalities. The partial recruitment or availability, of fish to the roe fisheries were formulated to increase with age and were set to 1 for age 6^+ and older. The proportion of age 2^+ fish which are mature also appears to vary among years (Haist and Stocker 1985) and some reduction fisheries targeted on immature 1^+ fish. To account for inter-annual variation in availability a modified logistic equation is fit over all age classes (1^+-10^{++}) and the inflection age for availability is permitted to vary from year to year but the slope is assumed constant:

$$l_{ij} = \frac{1}{1+\exp(-d(j-g_i))}$$

where d is the slope at the inflection age, and g_i is inflection age in year i. Estimated availability for ages 1^+ and 2^+ are presented in Figure 4. In the forecast year, the availabilities are set to the geometric mean over the last decade in the time series.

For the selective gillnet fishery (i.e. fishing period 3), fishing mortality is separated into age selectivity and fishing intensity components. Following Doubleday (1976),

$$\ln\left(F_{ij3}\right) = a_{i3} + b_j \tag{3.2a}$$

where a_{i3} represents the general level of fishing mortality due to the gillnet fishery in year i, and b_j represents the relative selectivity of the gear for age-class j. The b_j are parameterized such that age selectivity is modelled as a function of annual average weights-at-age. A modified logistic equation is used to describe the level of selectivity as a function of weight-at-age,

$$b_{ij} = \frac{1}{1+\exp(r - t\, g_{ij}^{w})}$$

where g_{ij} is $\log_e$ of the geometric mean weight-at-age j in year i. The b_{ij} replace the b_j in equation 3.2a.

For non-selective fisheries (i.e. fishing periods 1 and 2) only fishing intensity parameters are estimated, that is

$$\ln\left(F_{ijr}\right) = a_{ir}\,.$$

As in recent assessments, an average natural mortality parameter, $M_{\bullet}$, is estimated. It is assumed that most of the natural mortality occurs following spawning and over the course of the summer and early winter prior to the first fishery (period 1). Little or no natural mortality is assumed during the course of the roe fisheries (periods 2 and 3) which occur over a roughly 2 week period at the end of the year. Hence, various proportions of the annual natural mortality for the three fishing periods is modelled as,

$$M_1 = 0.95M_{\bullet}$$
$$M_2 = M_3 = 0.025M_{\bullet}$$

Additional structure is built into the model through the inclusion of annual spawn data (spawn index, I_i). Spawning occurs at the end of the year so the number of spawners at age *j* in year *i* (G_{ij}) is estimated by

$$G_{ij} = N_{ijp}\ \exp\left(-F_{ijp} - M_r\right) \qquad \text{where } j>1$$

and the spawning stock biomass, which is assumed to be proportional to egg production, in year *i*, $\left(R_i\right)$ is

$$R_i = \sum_j w_{ij} G_{ij},$$

where w_{ij} is the average weight-at-age *j* in year *i*. The errors in the spawn index observations $\left(I_i\right)$ are assumed to be multiplicative so that

$$I_i = q\,R_i \exp\left(x_i\right), \tag{3.3}$$

where *q* is a spawn conversion factor and x_i is a normally distributed random variable with mean 0 and variance s_1^2. The residuals from this relationship are presented in Figures 5 and 6.

For the model described above the parameters to be estimated are:

T_{i1} , for the first age class and all years *i*,
T_{ij} , for age classes 1^+ to *k* in the first year,
l_{ij} , from the logistic equation for years 1 to *n* for ages 1^+ to 10^+,
a_{ir} , for all fisheries for years 1 to *n* and periods 1 to 3,
$d, g_i, r, t, w, M_\bullet$ and *q*.

The l_{ij} are parameterized to constrain their values between 0 and 1. The parameter s_1^2 is not estimated in the reconstructions, but is fixed as discussed later on.

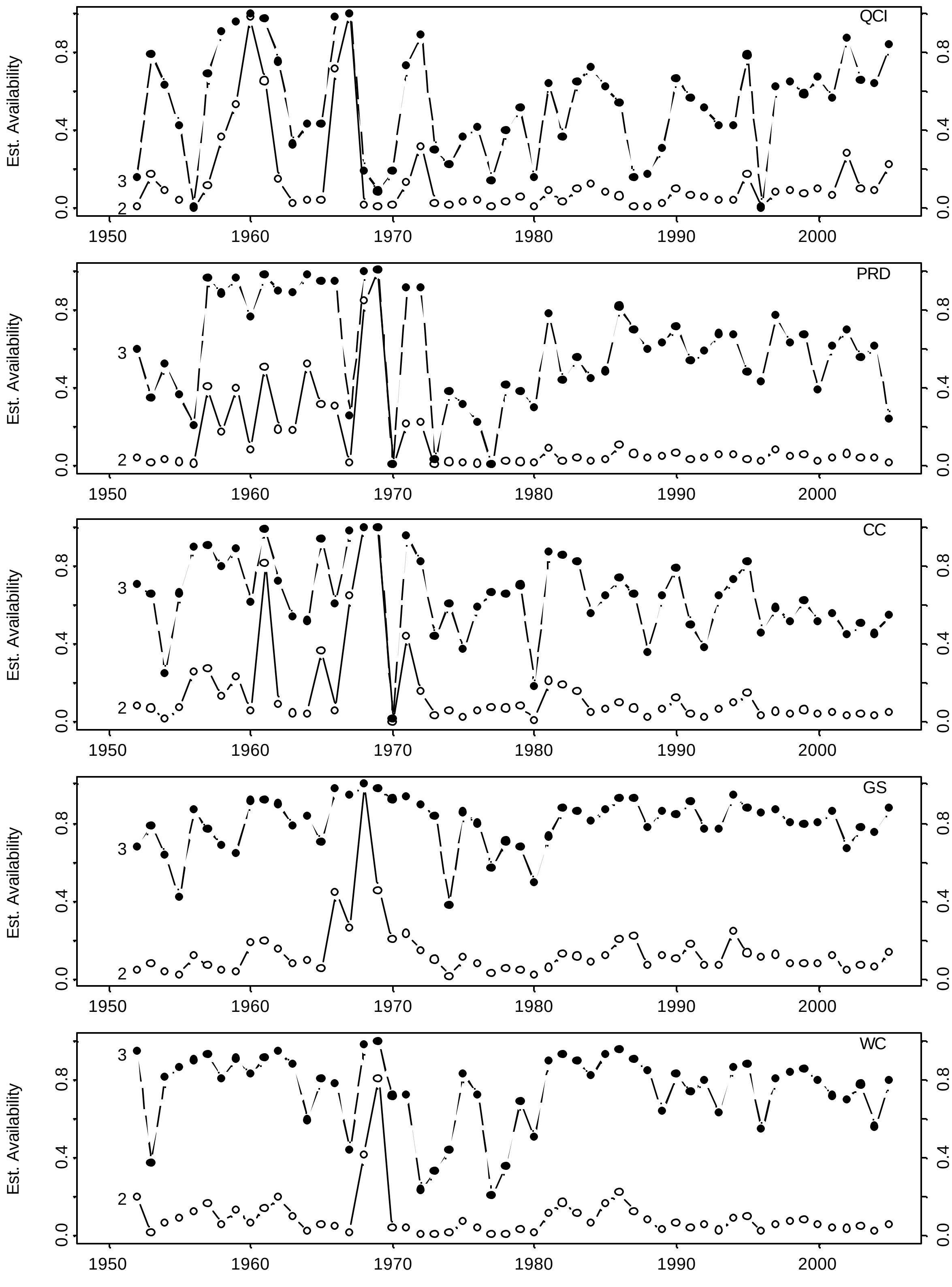

Figure 4. Estimated availability for age 2 and 3 fish in each season from 1951 to 2005 for each assessment region.

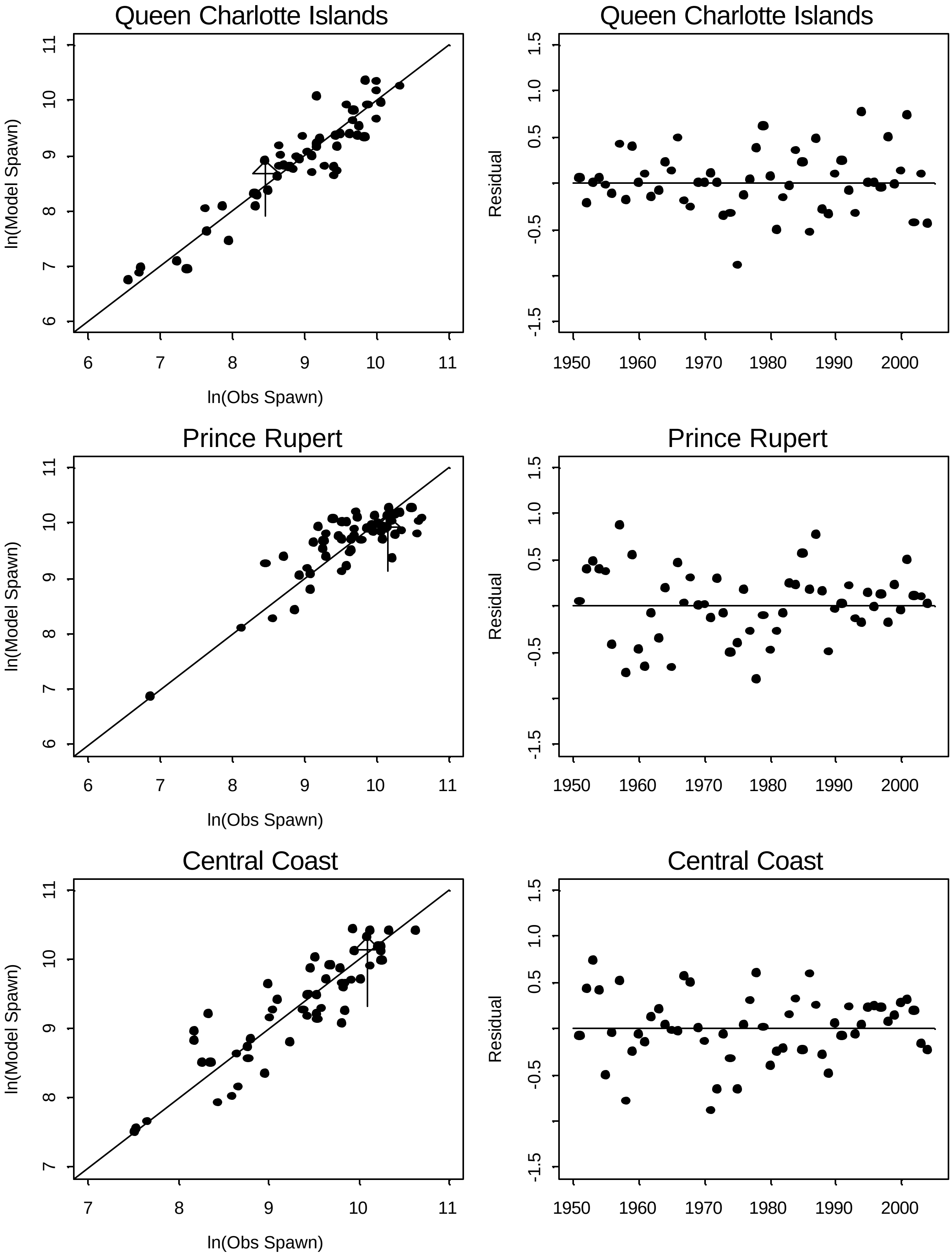

Figure 5. The residuals from the observed spawn - true spawn relationship for the northern assessment regions for the period 1951-2005. The arrow indicates the most recent data point.

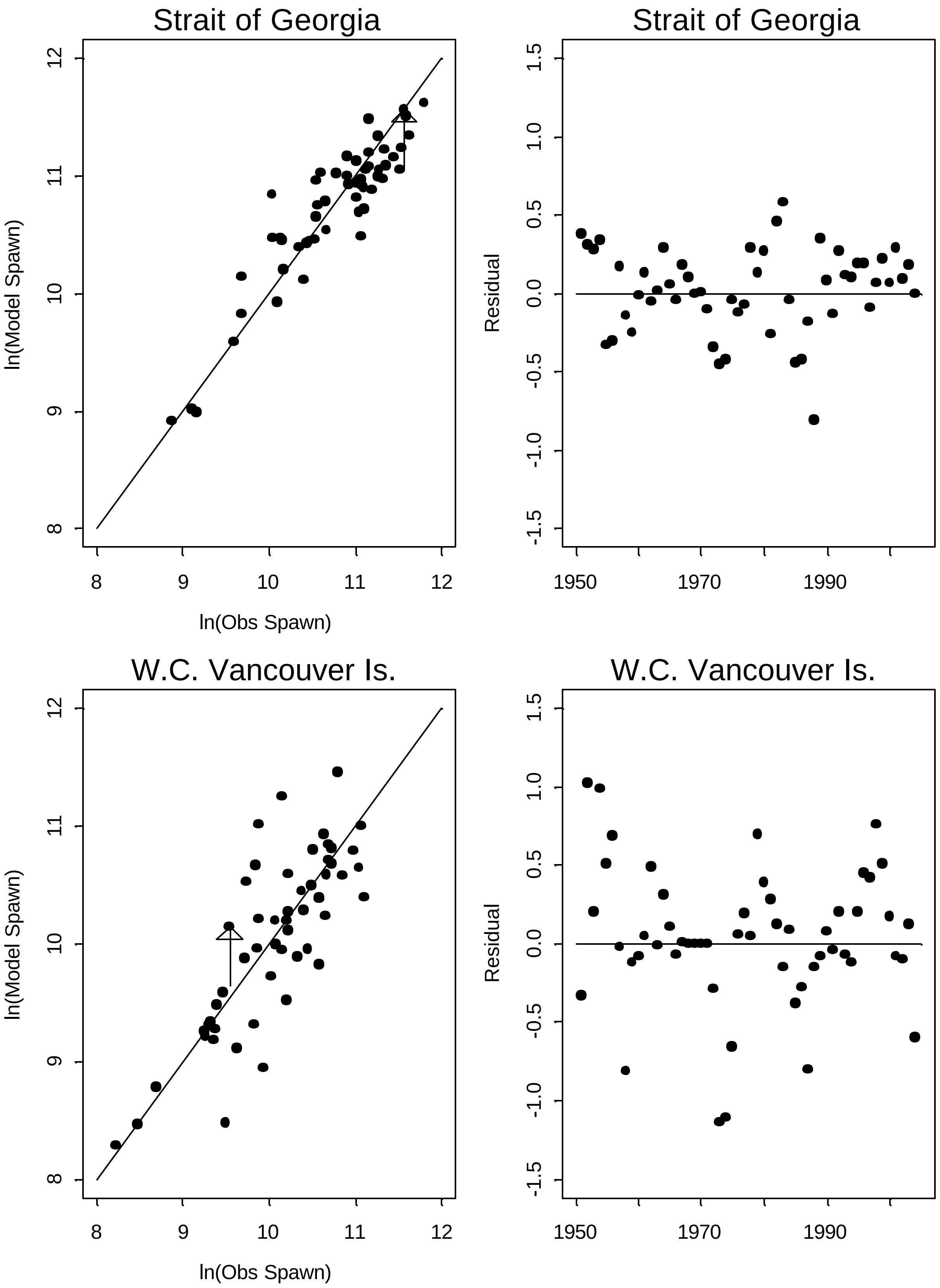

Figure 6. The residuals from the observed spawn - true spawn relationship for the southern assessment regions for the period 1951-2005. The arrow indicates the most recent data point.

The Objective Function

Data input to the stock reconstruction are:

S_{ijr}, the number of sampled fish aged j in year i for period r,
O_{ir}, the estimated number of fish caught in period r of year i,
I_i, the estimated escapement biomass or spawn index in year i,
w_{ij}, the mean weight-at-age j in year i,
g_{ij}, the $\log_e$ of the geometric mean weight-at-age j in year i.

The error structure suggested by Fournier and Archibald (1982) for the observations S_{ijr} and O_{ir} is used:

1) the S_{ijr} are obtained from ageing random samples of fish from the catch (and there are no ageing errors, i.e. a multinominal sampling distribution).

2) the error structure for the estimated number of fish caught (O_{ir}) is log-normal.

That is,

$$O_{ir} = C_{ir} \exp(x_i),$$

where C_{ir} is the actual number of fish caught in period r in year i ($C_{ir} = \sum_j C_{ijr}$) and the x_i are independent normally distributed random variables with mean 0 and variance s_3^2.

3) the random variables S_{ijr} and O_{ir} are independent.

Given these stochastic assumptions, the log-likelihood function (ignoring the constant term), for the parameters P_{ijr} $\left(P_{ijr} = C_{ijr} / C_{ir}\right), C_{ir}$, and s_3^2 is

$$\sum_{ijr} S_{ijr} \ln(P_{ijr}) - \sum_{ir} \frac{(\ln(O_{ir}) - \ln(C_{ir}))^2}{2s_3^2} \tag{3.5}$$

The assumption of log-normal measurement error in the observed spawn-actual spawn relationship introduces the following contribution to the log-likelihood function:

$$-\sum_{i} \frac{(\ln(I_i) - \ln(q\,R_i))^2}{2\,s_1^2} \tag{3.6}$$

The w_{ij} and g_{ij} are assumed to be estimated without error.

The objective function described above (eqn. 3.5 & 3.6) incorporates measurement error in the proportion at age data, the total catch data and the spawn index data, with the relative magnitude of the errors related through the variance terms s_1^2, s_3^2, and the sample sizes $\sum_r S_{ijr}$. Because there is not enough information in the data to estimate the relative error in these observations, the variance terms are not estimated but are held at fixed values. In recent assessments, the following variances were assumed:

$s_1^2 = 0.025$,
$s_3^2 = 0.0025$,

These correspond to approximately a 5% average error in estimates of the total number of fish caught and a 16% average error in spawn index observations. However, it is not possible to estimate the variance directly. Analyses presented in the 2003 assessment indicated that the model was relatively insensitive to the variance assumption and as a result a variance of 0.005 was assumed for both s_1^2 and s_3^2 and has been used in subsequent assessments.

The contribution to the objective function from the lack of fit for the age composition data for a fishery in period *r* in season *i* is given by:

$$V_{ir} = \sum_r S_{ijr} \ln P_{ijr} - \sum_r S_{ijr} \ln\left(\frac{S_{ijr}}{\sum_r S_{ijr}} \right)$$

The second term in this equation is a constant. Inclusion of this term allows comparison of the contribution to the lack of fit for the age composition data for each fishery. If the predicted and observed proportion at age data were identical, the V_{ir} would be zero.

To facilitate an assessment of the lack of model fit to the age composition data the standard deviates of the observed versus predicted proportions-at-age (Z_{ijr}) are also calculated:

$$Z_{ijr} = \frac{S_{ijr} - \left(\sum_r S_{ijr} \right) P_{ijr}}{\sqrt{S_{ijr} \left(1 - \frac{S_{ijr}}{\sum_r S_{ijr}} \right)}}$$

The residuals from the model fit to the age composition data are presented in Figures 7-11.

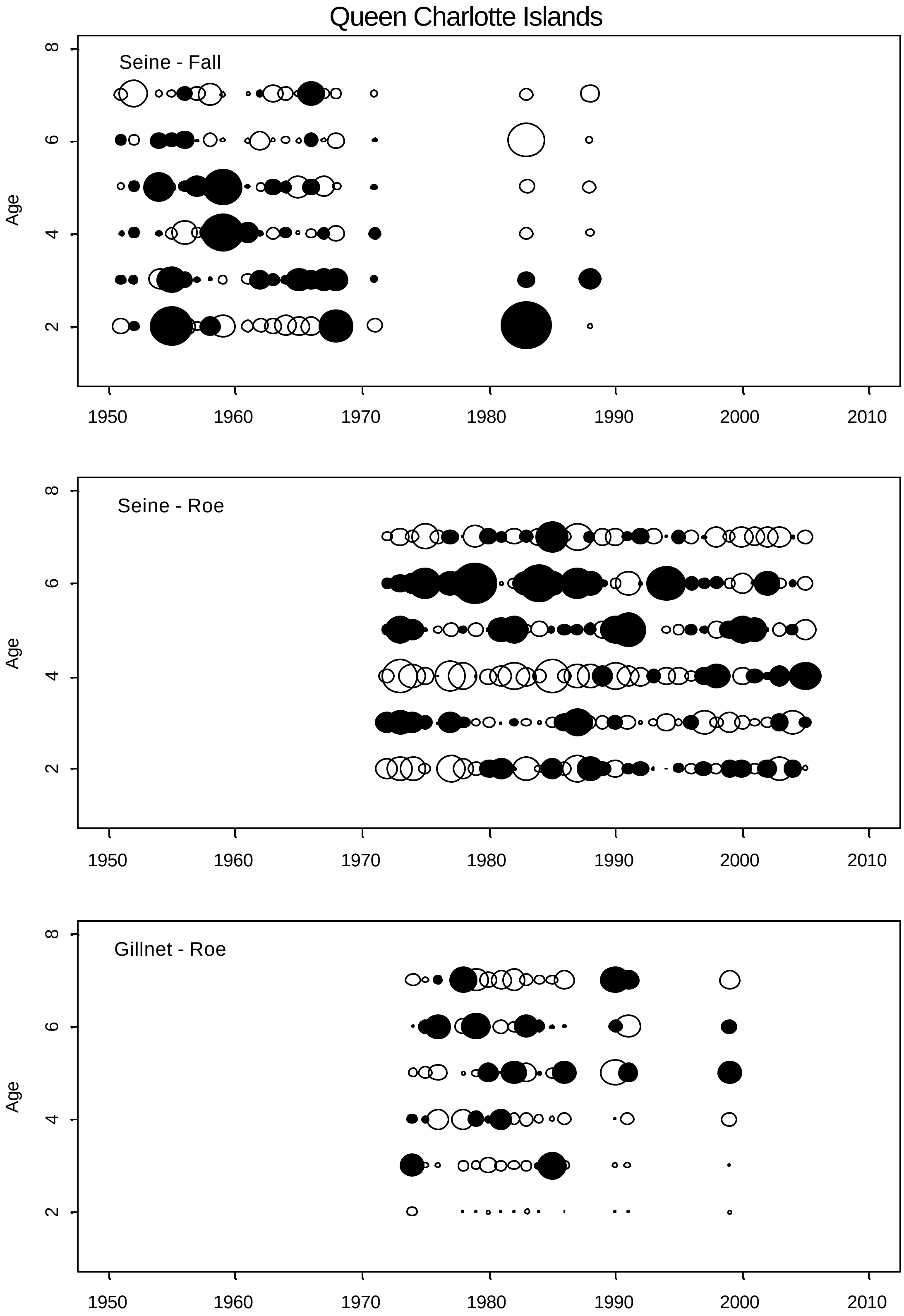

Figure 7. Residuals from the age-structured model fit to the catch-at-age data by year and fishing period for the Queen Charlotte Islands, 1951-2005.

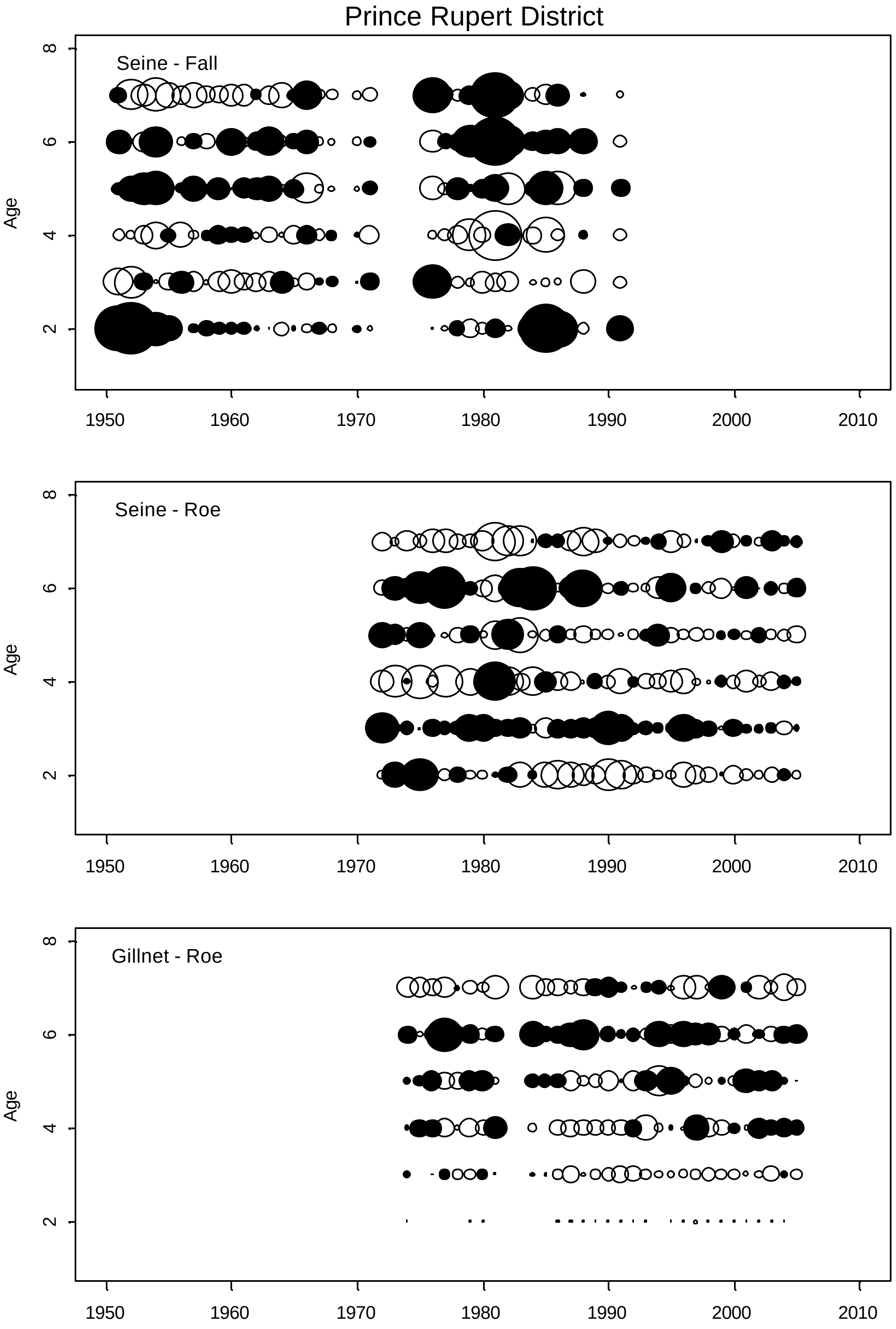

Figure 8. Residuals from the age-structured model fit to the catch-at-age data by year and fishing period for the Prince Rupert District, 1951-2005.

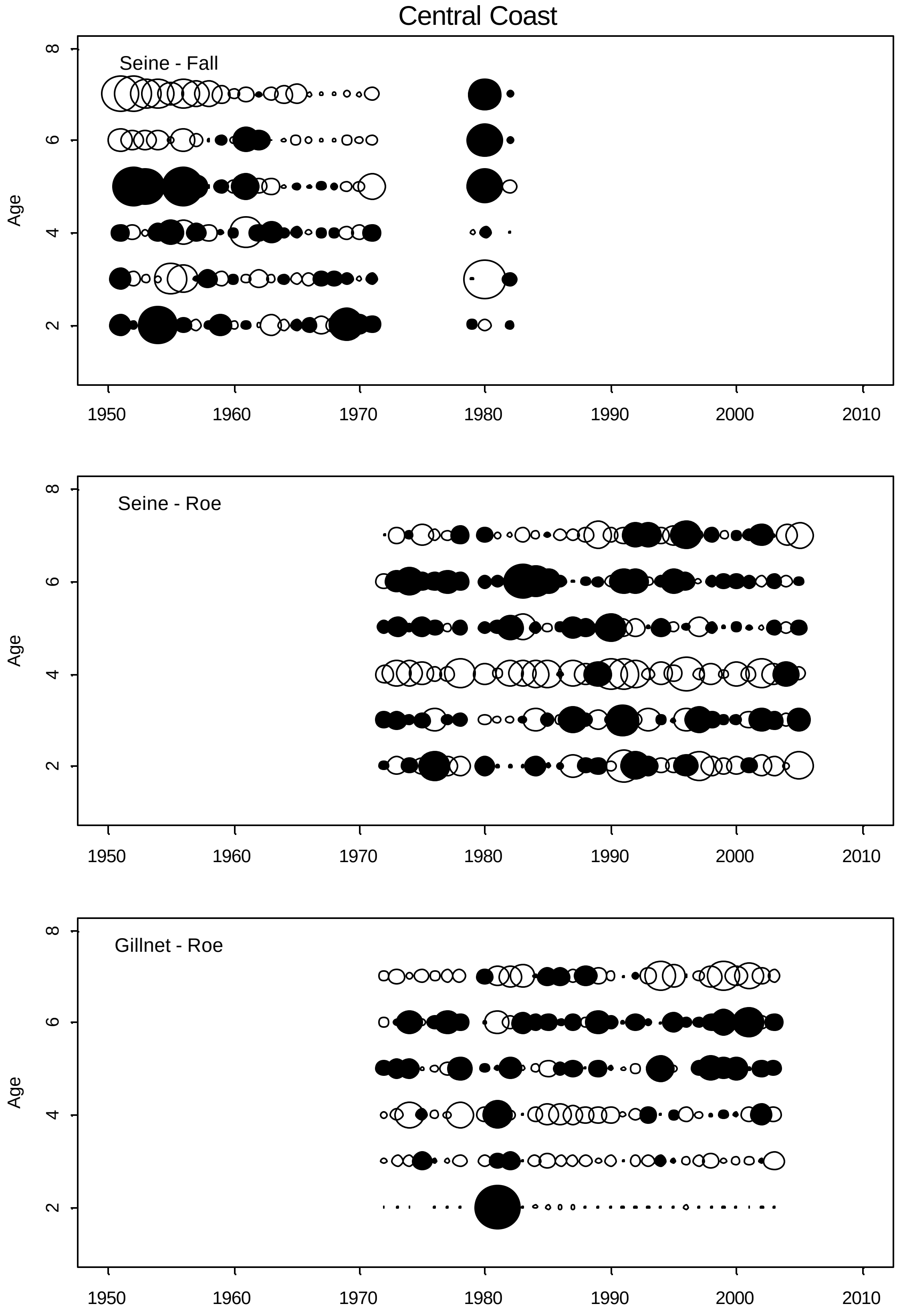

Figure 9. Residuals from the age-structured model fit to the catch-at-age data by year and fishing period for the Central Coast, 1951-2005.

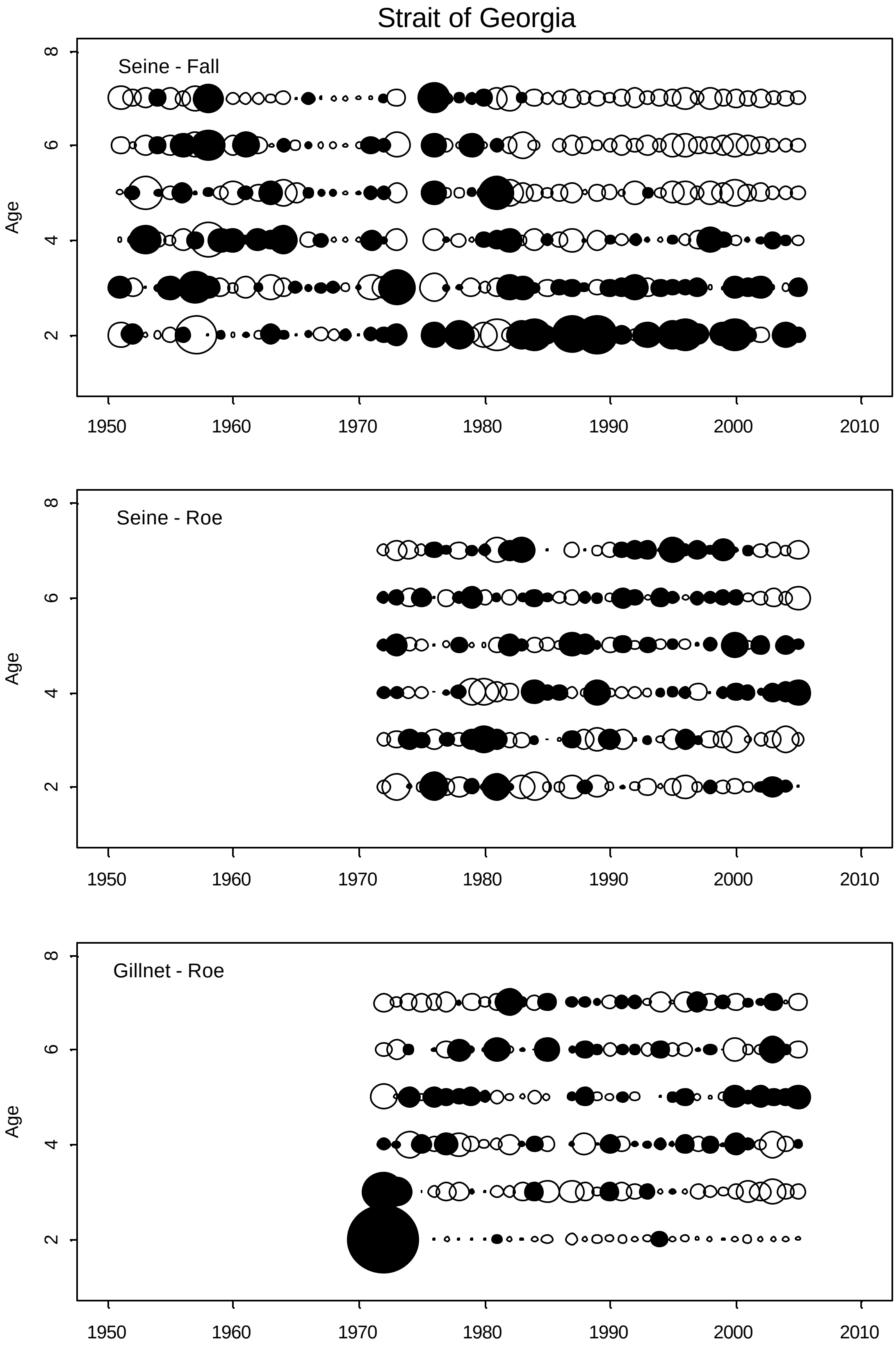

Figure 10. Residuals from the age-structured model fit to the catch-at-age data by year and fishing period for the Strait of Georgia, 1951-2005.

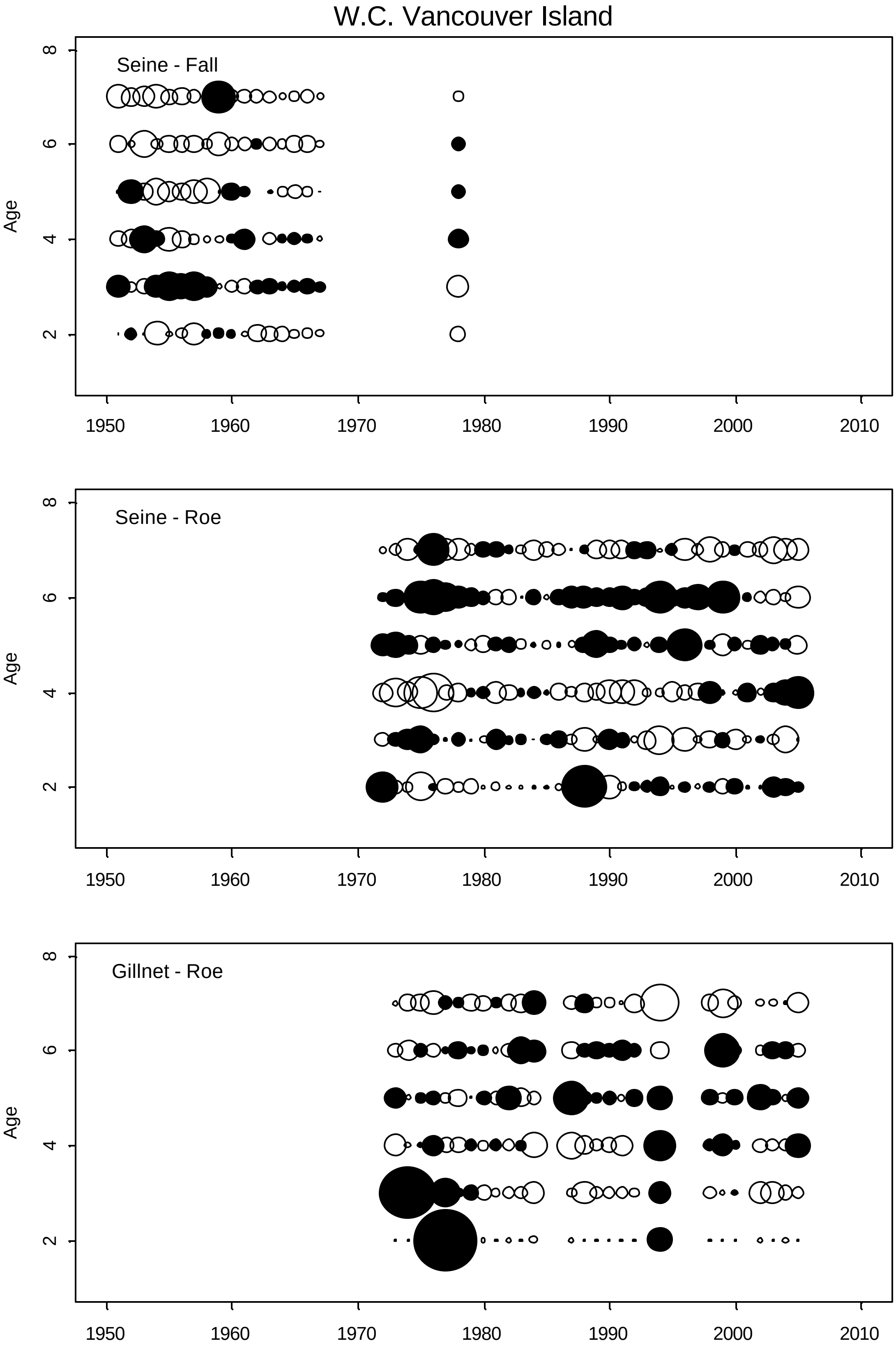

Figure 11. Residuals from the age-structured model fit to the catch-at-age data by year and fishing period for the west coast of Vancouver Island, 1951-2005.

4. ABUNDANCE FORECASTS AND POTENTIAL HARVEST

Forecasts of pre-fishery spawning stock abundance are determined only for the five major migratory stocks. Abundance forecasts are calculated in two ways. First, the numbers of fish at age prior to the roe fisheries are the numbers estimated at the end of the previous year or beginning of the current year multiplied by survival for the first period and by the estimated availability at age. The estimate of recruitment is based on the survival and availability of the age 1^+ fish for the previous year. This recruitment is added to the estimated returning adults to project total abundance. Marginal likelihoods or Markov Chain Monte Carlo (MCMC) simulations are used to determine likelihood profiles for the current biomass and for the predicted total biomass. The second forecast of abundance is determined as in previous assessments for three recruitment scenarios based on estimated numbers-at-age 2^+ for the 1951-present time series. Poor, average, and good recruitment levels are calculated as the mean of the lowest 33%, the mid 33%, and the highest 33% of the estimates of historic age 2^+ abundance. These three recruitment estimates are then added to the projected adult biomass in the coming year to provide abundance forecasts under scenarios of poor, average, or good recruitment.

Forecasts of abundance for minor stocks are not currently possible. In the absence of additional information it is assumed that the abundance of herring in the minor stock areas (Areas 2W and 27) in the coming year will be equivalent to that estimated in the previous year.

Abundance Forecasts

The abundance of short-lived species such as Pacific herring is heavily influenced by annual fluctuations in recruitment. As a result, accurate forecasts of recruitment are critical to accurate forecasts of total stock abundance. Predicting recruitment for Pacific herring and most other fish species is difficult. Therefore, the scientific advice on the forecast of stock abundance is heavily dependent on the assumption made about recruitment strength. In the absence of independent information, the scientific advice has been to assume an average recruitment to minimize forecasting errors. Currently, forecasting methods for two stocks (west coast Vancouver Island and Strait of Georgia) have been tested and validated for routine use by PSARC. This forecast relies upon independent, offshore survey data collected during the summer prior to the recruitment of age-2^+ fish to the spawning population. Recruitment forecasting methodologies are also being developed for other herring stocks but none are currently in routine use. Therefore, a decision on the level of recruitment to be used in the forecast must be made in the absence of independent data. The decision about recruitment strength must be consistent with the precautionary approach to fisheries management while assuring harvest opportunities are not unduly restricted.

In the absence of alternative recruitment forecasting methods, the following rules have been adopted in developing the abundance forecast:

1. If the pre-fishery biomass was below Cutoff in the previous year, then assume POOR recruitment for the forecast.

2. If the pre-fishery biomass was above Cutoff in the previous year and recruitment has been GOOD in the two previous years, then assume GOOD recruitment for the forecast.

3. If Rule 1 or Rule 2 DO NOT APPLY then assume AVERAGE recruitment for the forecast. The modified harvest rule may apply.

These decision rules provide a consistent approach to determining the recruitment assumption to be used in the annual forecasts.

Management Considerations

The Pacific Science Advice Review Committee (PSARC) has reviewed the biological basis for target exploitation rate, considering both the priority of assuring conservation of the resource and allowing sustainable harvesting opportunities (Schweigert and Ware 1995). The review concluded that 20% is an appropriate exploitation rate for those stocks that are well above Cutoff or minimum spawning biomass threshold levels (Rice et al. 1996). The 20% harvest rate is based on an analysis of stock dynamics which indicates this level will stabilize both catch and spawning biomass while foregoing minimum yield over the long term (Hall et al. 1988, Zheng et al. 1993). A fixed escapement policy would theoretically produce higher yields and spawning stock stability but is not readily attainable at the operational level. In addition to the 20% harvest rate, a Cutoff level set at 25% of the estimated unfished biomass level is used to ensure that adequate spawning biomass to sustain each population during natural reductions in stock productivity, is maintained for each stock. To increase the probability that spawning biomass will be maintained above the Cutoff level, for those stocks which are marginally above Cutoff the following reduced catch level is recommended:

Catch = Forecast Run - Cutoff.

This will provide for smaller fisheries in areas where the 20% harvest rate would result in escapement levels below the Cutoff.

Cutoff levels have been established through a stock-recruitment curve or bootstrapping of the observed recruitment time series. Changes in model structure have historically resulted in a parallel change in Cutoff level. To minimize confusion, in 1995 the Subcommittee recommended that a fixed Cutoff level should be established for each stock based on the long-term production characteristics in relation to current environmental conditions and that this Cutoff level need not be re-evaluated on an ongoing basis. The Cutoff levels for the five major migratory stocks are:

	1992/93 Cutoff[a]	1994/95 Cutoff	1996/97 Cutoff	**Current Cutoff**
Queen Charlotte Islands	11700	10700	10700	**10700**
Prince Rupert District[b]	12100	12100	12100	**12100**
Central Coast	10600	18800	17600	**17600**
Strait of Georgia	22100	21200	21200	**21200**
W.C. Vancouver Island	20300	18800	18800	**18800**

[a] - Cutoff level based on simulation model with stock-recruitment relationship, and two assessment areas on the WCVI.

[b] - Because of the poor performance of the age-structured model in this region in the past the Cutoff has not been recalculated using the bootstrap approach but is based on a stock-recruitment relationship.

The chronology of catch forecasts, recommended quotas, and roe fishery harvests since the introduction of the Cutoff in 1986 is presented in Table 4.2.

It is important to note that the current Cutoff represents a commercial fishery fishing threshold rather than a conservation threshold or reference point. It is a reference point intended to maintain the reproductive capacity of the stock. Thus, even when a stock is near (or below) the stock-specific Cutoff, conservation concerns may be unwarranted as this information alone is insufficient to conclude that a stock may be at risk. The current commercial fishery Cutoff is used to maintain stock productivity or rebuild stock biomass following years when stock size decreases below the Cutoff.

The harvest of minor stocks is also conducted in a precautionary manner given that no forecast of abundance in the upcoming season is currently possible. The harvest rule for minor stocks is that a maximum of 10% of the estimated abundance in the current season may be harvested in the coming season. The harvest rule is based on a concensus by the PSARC Subcommittee that this level of removal is sustainable. The harvest rule is based on the assumption that minor herring stock dynamics are consistent with the major migratory stocks which can sustain substantially higher rates of harvest (Hall et al. 1988, Zheng et al. 1993).

5. ACKNOWLEDGEMENTS

The Pelagics Subcommittee of PSARC and reviewers have provided helpful critique of the assessment model and its assumptions resulting in ongoing modifications and improvements to the model. Chuck Fort and Peter Midgley have ably verified and updated the catch, biological sampling and spawn survey data bases on an annual basis. Howard Stiff provides ongoing programming support for the Access databases used to summarize the assessment data series. Database upgrades and ongoing maintenance has been funded by the Herring Conservation and Research Society (HCRS). The HCRS through the test fishing program also funds the collection of spawn survey information and test fishery biological samples coastwide that are critical to the annual assessment. The Ageing laboratory at PBS continues to provide timely ageing information.

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Table 4.2. Stock biomass forecast, recommended yield, actual roe fishery quota, and roe catches (tonnes x 1000) since 1986.

		1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999[d]	2000[d]	2001[d]	2002[d]	2003 [d]	2004[d]
QCI [e]	Forecast[a]		15.3	12.1	13.7	35.3	23.2	18.1	17.7	12.4	7.7	6.7	11.0	19.8	28.2	15.1	8.7	14.0	7.2	12.7
	Rec. Yield[b]		2.2	0.0	2.7	7.1	4.6	3.6	3.5	1.0	0.0	0.0	0.3	4.0	5.6	3.0	0.0	2.8	0.0	2.0
	Roe Quota	3.8	1.4	0.0	0.9	5.5	4.7	3.3	3.0	0.0	0.0	0.0	0.0	1.6	3.0	1.4	0.0	0.4	0.0	0.0
	Roe Catch[c]	3.6	2.0	0.3	1.4	9.0	7.0	3.8	4.0	0.3	0.0	0.0	0.0	1.4	3.0	1.8	0.0	0.7	0.0	0.0
PRD	Forecast[a]		32.1	43.8	42.6	23.3	19.4	30.5	55.1	34.1	21.9	21.2	36.1	34.0	24.4	37.0	23.2	34.1	31.7	40.7
	Rec. Yield[b]		6.4	8.7	8.5	4.7	3.9	6.1	11	6.8	4.4	4.2	7.2	6.8	4.9	7.4	4.6	6.8	6.3	8.1
	Roe Quota	6.4	5.4	7.5	7.3	3.5	2.6	4.2	5.4	4.9	2.3	2.4	5.5	5.5	2.0	4.1	2.5	4.2	3.5	4.1
	Roe Catch[c]	8.3	6.1	7.9	8.5	4.9	3.5	5.0	6.3	4.7	2.1	3.1	5.5	3.2	2.1	4.3	2.9	4.5	3.7	4.1
CC	Forecast[a]		23.0	23.8	48.5	43.2	38.2	37.7	70.1	69.8	54.4	25.8	20.7	44.5	43.4	47.0	36.8	25.4	25.3	36.6
	Rec. Yield[b]		4.6	4.8	9.7	8.6	7.6	7.5	14.0	14.0	10.9	5.2	3.1	8.9	8.7	9.4	7.4	5.1	5.0	7.3
	Roe Quota	2.3	3.3	3.7	7.8	7.4	6.2	5.3	7.8	10.3	8.5	3.2	1.4	7.8	6.9	6.3	5.2	2.8	2.1	2.3
	Roe Catch[c]	3.3	3.6	4.5	9.5	8.4	8.9	8.3	10.5	11.9	9.6	4.3	3.6	8.6	7.5	7.4	6.1	3.3	2.2	3.0
SG	Forecast[a]		53.0	46.7	49.4	55.2	69.8	59.2	91.8	97.4	69.5	63.4	77.2	72.7	78.9	84.7	82.6	103.1	130.0	156.4
	Rec. Yield[b]		10.6	9.3	9.9	11.0	14.0	11.8	18.3	19.5	13.9	12.7	15.5	14.5	15.8	16.9	16.5	20.6	26.0	31.3
	Roe Quota	0.0	8.0	6.4	7.4	7.1	9.1	9.7	11.0	14.4	11.9	10.8	13.2	13.0	11.5	13.2	13.9	16.2	16.8	16.1
	Roe Catch[c]	0.2	9.1	7.5	7.4	7.9	10.6	12.5	13.1	16.7	12.5	13.6	15.4	12.7	11.8	14.0	15.0	17.3	17.8	12.2
WCVI [f]	Forecast[a]		48.3	39.6	52.6	35.9	33.9	29.1	NA[g]	36.3	20.8	21.4	24.1	40.1	39.6	21.5	14.6	22.4	30.0	33.7
	Rec. Yield[b]		9.7	7.9	10.5	7.2	6.8	5.8	3.4[g]	7.3	2.0	2.0	4.8	8.0	7.9	2.7	0.0	3.6	6.0	6.7
	Roe Quota	0.0	9.4	8.1	10.3	7.2	6.7	2.9	2.7	5.0	1.3	0.9	3.7	7.5	5.1	1.1	0.0	0.4	2.9	4.3
	Roe Catch[c]	0.2	15.9	9.7	13.4	9.9	8.6	3.7	5.6	6.0	2.0	0.8	6.7	7.0	4.4	1.6	0.0	0.8	3.0	4.5
Coast	Forecast		171.7	166.0	206.8	192.9	184.5	174.6	234.7	250.0	174.3	138.5	169.1	211.1	214.5	205.3	165.9	199.0	224.2	280.1
	Rec. Yield		33.5	30.7	41.3	38.6	36.9	34.8	50.2	48.6	31.2	24.1	30.9	42.2	42.9	39.4	28.5	38.9	43.3	55.4
	Roe Quota	12.5	27.5	25.7	33.7	30.7	29.3	25.4	29.9	34.6	24.0	17.3	23.8	35.4	28.5	26.1	21.6	24.0	25.3	26.8
	Roe Catch	15.6	36.7	29.9	40.2	40.1	38.6	33.3	39.5	39.6	26.1	21.8	31.1	32.9	28.8	29.1	24.0	26.6	26.7	23.8

[a] PSARC stock forecast used to derive recommended yield;

[b] PSARC recommended yield, includes allocations to non-roe fisheries;

[c] Roe catch includes all test fishery catches;

[d] Catch in 1999 through 2004 are the dockside validated catch;

[e] In 1990 to 1993 catch for QCI included both areas 2E and 2W;

[f] Includes Area 27 catch in 1983 & 1984 but excludes it in 1992, 1993, 1994, 1995 following removal from assessment region;

[g] No consensus on stock status, recommended that catch not exceed 1992 level.